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Energy management based on productiveness concept

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ABSTRACT

This paper presents a method based on a new interpretation of the concept productiveness in order to manage local energy resources through smart loads. The assumption that electricity demand is almost completely inelastic is changing as a result of deregulated wholesale markets. In this line, the smart building and plug-in hybrid electric vehicle promise flexibility of building energy and comfort management.

Productiveness as defined in this paper is a means of meeting two objectives: cost and quality for a group of electrical charges with renewable penetration and/or real-time prices. This concept assesses how well one unit of energy (kWh) performs the task that it has been assigned, but it is not an econometric model for forecasting demand. The concept of productiveness according to the focus of the present study permits the users to monetarily evaluate the use of their electrical energy, enabling the management of different loads. As a starting point, in the simulations presented in the framework of a bioclimatic building and electric vehicles, this new interpretation responds as expected.

Contents

1. Introduction

In accordance with recent studies [1,2] the production of renewable energies in Europe, and more specifically in Spain, would increase their contribution to the total energy consumption from 10.5% in 2008 to 22.7% in 2020.

However, and due to the random nature of renewable energy sources (RES) [3], it is necessary to develop energy-demand management strategies which enable the final user to participate actively in the electric market, gaining more flexible energy demand [4,5].

In 1980, Schweppe et al. [6], introduced the term FAPER (Frequency Adaptative Power Energy Rescheduler) to indicate the improvement in the balance between intermittent production of RES and energy demand. This consists of adjusting the demand of each user to the local frequency, just as the primary control of the electric plant would do in 5-min intervals or more.

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Nomenclature

A	Coefficient of the thermal losses, in kW °C^{-1}.
c_0	Energy cost, in €·kW h^{-1}.
x	Variable of state of the process
k_0	Event start time, in number of sampling periods.
k	Duration of the disturbance, in number of sampling periods.
k_e	Duration of the disturbance, in number of sampling periods.
m	Productiveness slope, in €·°C^{-1}.
t_D	Desired instant for the end of the charge, in min.
t_{min}	Minimum time to reach the total charge with maximum power, in min.
t_S	Instant of starting the charge, in min.
T	Temperature, in °C.
T_D	Desired temperature, in °C.
T_O	Outdoor reference temperature, in °C.
T_{OFF}	Temperature of the disconnected process, in °C.
T_S	Sampling period, in min.
SoC_{min}	Minimum state of charge in the accumulator, in kWh.
$SoC(t)$	State of instantaneous charge in the accumulator at the instant t, in kWh.
$SodC(t)$	State of desired charge in the accumulator at the instant t, in kWh.
$SoTC$	State of total charge in the accumulator, in kWh.
p	Productiveness, in €·kW h^{-1}.
P	Power of an electric load, in kW.
$P_{max\text{-}char}$	Maximum power to charge accumulator, in kW.
$P_{max\text{-}dischar}$	Maximum power to discharge accumulator, in kW.
$Prod$	Production in €.
V	Room volume, in m^3.
ΔP_i	Variation of power in the load i, in kW.
ΔP_T	Variation of total power, in kW.
η	Charge performance.
τ	Time constant of the process, in min.

Recently, in the Olympic Peninsula (state of Washington, USA), due to the progressive penetration of renewable and intermittent resources, a demonstration project of a local market of charges and small generators was launched, showing promising advances in the integration of RES [7].

One study [8] stated that any load that has an internal temperature control can be regulated, given that it represents an accumulation of thermal energy. Applications such as air conditioning, heat pumps, refrigerators, heating, etc. can be controlled. If the accumulation capacity is considered, the accumulators of electric energy themselves are controllable loads [9–11]. So, the smart building and plug-in hybrid electric vehicle (PHEV) are two promising technologies to meet this objective. The integration of both emerging technologies holds great promise for improving the power-supply reliability and the flexibility of building energy and comfort management [12–15]. For this it is necessary to review current models of market and business [16].

Energy storage in the form of thermal energy in buildings [17,18], or chemical energy in PHEV, can store the renewable energy generated [19–23], while smart buildings can optimise their comfort conditions. Other applications include greenhouses, which also have renewable production and air-conditioning systems [24–27].

Given the random nature of renewable sources, it is necessary for demand to be more flexible and to encourage the user to participate actively in the electric market [4,9,28–31]. The main indicator of the balance between production and demand is the frequency, and therefore strategies are proposed to fit the load to its fluctuations [6,32–35]. Several authors ([36–39]) have approached the problem of including domestic load, which they classify as critical and controllable.

A different paper [40] introduced the term GridFriendly^{TM} loads, indicating that such loads offer an increase in renewable resources by contributing to the primary control of the frequency of the system. This concept permits adjusted consumption of renewable energies imposed by the needs of the grid. In addition, users optimise consumption according to their needs and their renewable production, thanks to the flexibility of their consumption [12].

In the study of the flexibility of demand, two work lines can be followed according to which part imposes the power adjustment:

1. *Adjustment of consumption according to the needs of the grid*. As described in the literature [8,40,41], the load can help to manage systems with large degree of renewable penetration [35]. In addition to the flexible demand, a system of incentives is needed, according to other authors [4,29,42,43], since there are goals sought by the consumer and the energy distributor such as user comfort, reduction of energy losses in the grid, or economic profit [42]. In yet another study [43], the electric vehicle is considered capable of assuming the portion of the market related to regulation and spinning reserves, invariably under the settings selected by the operator of the system. The term demand response (DR) refers to the adjustment made by the user in response to the variable pricing according to the time of use [44–47]. Also, some studies [35,48–50] discuss the need for the user to know the price of the energy in real time and to adjust consumption accordingly. On the same subject, in [51], it is stated that the electricity prices provide incentives to consume electricity when the supply of renewable generation is high.
2. *Adjustment of consumption according to the user's needs*. An intelligent building has heating, ventilation, and air conditioning (HVAC) [15], as well as accumulators for vehicles (electric or hybrid) [12], and makes use of self-produced renewable energy. The function of the control of the building is to optimise the objectives: first of all, service quality (e.g. comfort) and energy cost.

Questions remain concerning how best to encourage both consumer and business participation in these markets [52]. The problem to resolve is posed in the following way: in response to an event, the consumer's power needs to be increased/ decreased according to the portion of flexible demand. It is necessary to establish a criterion to modulate the consumption of several loads and to decide which and how much to increase/ decrease in power.

One approach consists of resolving a multi-objective problem and optimise costs (power and/or energy consumed) and quality (e.g. user comfort), as a response to the event. The main drawback is that cost and quality are of different magnitudes.

The aim of the present paper is to develop a single function that enables the assessment of the objectives: cost and quality of a unit of electrical energy. A concept that relates cost with a production unit is productiveness, we want to provide an interpretation for apply it in electric loads.

The paper is organised as follows: Section 2 defines productiveness for a unit of energy (kWh) and then to evaluate its

application to different loads. In Section 3 the developed optimisation approach is described and briefly introduces the facilities where this work has been developed: the research framework and the CDdI-CIESOL-ARFRISOL building. Section 4 is devoted to presenting the preliminary results from a simulation. Finally, in Section 5, the main conclusions and future works are summarised.

2. Concept of productiveness of a unit of energy

Studies [53,54] have defined productiveness losses of conditioned air according to the index PMV (Predicted Mean Voted [13]). It bears mentioning that productiveness in these terms refers to the final product, in this case salary losses of the employees.

Schweppe [48] proposed a penalisation function (bathtub) to get a multi-objective goal. The meaning of the above multi-objective function is similar to proposed approach in this paper because it optimises cost and quality of the electric energy using weighting coefficients. These coefficients do not have physical information, for example, if it is applies to cost-weigh 80%, it does not know what effect will this action have on the quality, and vice-versa.

We define productiveness as follows: a unit of energy (kWh) is 100% productive when applied to maintain the conditions defined in settings and timing established.

In other words, the final user is willing to pay an economic cost c_0, per each kWh consumed in order to maintain the desired comfort conditions. Productiveness defined in these documents refers exclusively to the resolution of the ‘‘task’’ assigned to each unit of energy. This does not refer to an econometric model [55].

In this paper, it is looking for that weighting coefficient will be only one, productiveness and it has its own meaning. The last definition is a generic concept, but mathematical expression is particular to each type of load. In this work it is proposed for two types of loads: thermals (HVAC systems) and accumulators for electric vehicles.

2.1. Productiveness in thermal loads

The consumer is willing to pay a cost c_0 per kWh when applied to the desired conditions (desired temperature, T_D), but is unwilling to pay anything to maintain the conditions that exist when the appliance is disconnected (temperature of the disconnected process, T_{OFF}). Therefore, the first kWh applied to the HVAC system is 0% productive and when the conditions of the settings are reached, the kWh applied to maintain it is 100% productive.

The limits of productiveness for any temperature T, will be:

1. If the temperature is equal to T_D, point A in Fig. 1, the kWh produces what it costs, c_0.
2. If the temperature is equal to T_{OFF}, point B in Fig. 1, the kWh produces nothing.
3. If the temperature is higher to T_D, zone II in Fig. 1, in this case a symmetrical curve is proposed, but it can be modified according the user's preferences. In this case, productiveness declines in both cases when not reached or when it exceeds the desired temperature, T_D.

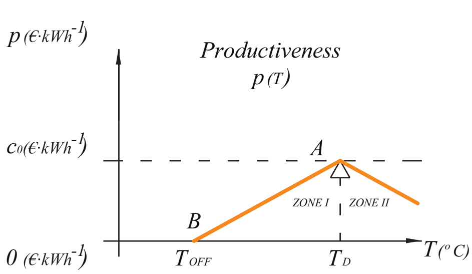

Fig. 1. Productiveness in thermal loads, HVAC.

Eq. (1) represents the expression of productiveness per unit of energy. Fig. 1 shows a heating process because $T_{OFF} < T_D$, and cooling process occurs when $T_{OFF} > T_D$. Eq.(1) is identical in both cases.

$$p(t) = c_0 - m|T - T_D| \quad where \quad m = \frac{c_0}{|T_{OFF} - T_D|} \tag{1}$$

where m is productiveness slope in $€ \cdot °C^{-1}$.

2.2. Productiveness in Accumulators for electric vehicles

The productiveness of this type of load is associated with the fact that the accumulator is available (charged) over time [45]. The accumulator will be used as a flexible load by which energy is given to or taken from the grid according to vehicle to grid (V2G) technology [21,43]. The productiveness of the accumulator as an electric load is associated with the time points of connexion, t_S and disconnexion t_D, provided that the difference between the two is greater than the minimum charge time t_{min}, (Fig. 2). Thus, from the starting time, the battery will have as a desired charge at each point in time $SodC(t)$ a straight line that connects the points (t_S, SoC_{min}) and (t_D, $SoTC$), as shown in Fig. 2:

So, the limits of productiveness for any point in time t such that, $t_S < t < t_D$, and with the instantaneous state of charge in the accumulator $SoC(t)$, will be:

1. If the battery is totally discharged (0% charged, minimum state of charge SoC_{min}), the productiveness of the kWh will be maximum given that any kWh applied will be accumulated, point A in Figs. 2 and 3.
2. If the battery has the desired state of charge $SodC(t)$, the kWh produces what it costs, c_0, point B in Fig. 3.
3. The state of instantaneous charge $SoC(t)$ correspond with point C in Figs. 2 and 3.
4. If the battery has reached its total state of charge $SoTC$ (100% charged), the productiveness of the kWh will be null, given

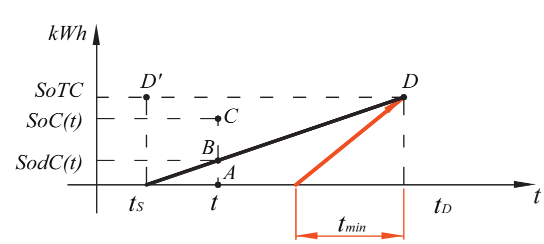

Fig. 2. Expected state of charge in the accumulators.

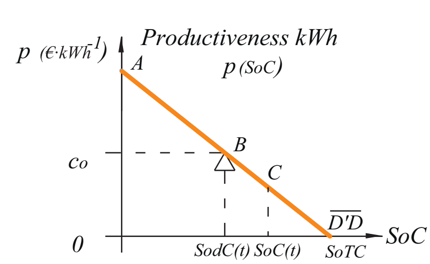

Fig. 3. Productiveness in accumulators for electric vehicles.

that any extra kWh will not be stored. This is true at any instant t, and corresponds to points on the line DD' in Fig. 2 and point $D'D$ in Fig. 3.

Based on these features, the Productiveness in accumulators for electric vehicles can be defined by the linear equation (Eq. (2)):

$$p(SoC) = c_0 \frac{SoTC - SoC(t)}{[SoTC - SodC(t)]} \tag{2}$$

3. Management of different loads using productiveness

The aim of our work is to apply the concept of productiveness to simple case, as described in this article. To do so, let us pose a particular problem, e.g. a cloud passing over a photovoltaic park, to verify the effectiveness of the proposed approach or not in this case at least. It is necessary to absorb a ΔP_T at a point in time k_0 and during k_e sampling periods (T_S equal 5 to 15 min [6]), to respond to an event [56]. It is not possible to optimise a future cost function because the duration of the interference k_e is not known beforehand. At each time point k, only the immediate period will be evaluated $(k+1|k)$. This is maintained over the k_e periods of the duration of the disturbance.

It is solved in two ways: equality of partial-production rates, and optimisation of total production.

3.1. Equality of partial-production rates

The partial production is defined to each process i (Eq. (3)). This is caused by the user when controlling the process i to respond to the disturbance.

$$\Delta Prod_i = p_i \Delta P_i T_m \quad (€) \tag{3}$$

The objective of the controller (J_1) in this case is for all loads support the same effort caused by its control signal ΔP_i. This equations system is solved subject to a constant variation of power (ΔP_T), and equal to the initial variation at the time point k_0. It takes the following form for N loads (Eq. (4)):

$$\forall t \mapsto k_0 T_m \le k T_m \le (k_0 + k_e) T_m$$

$$Min\ J_1 = \left[\sum_i^N \sum_{j \ne i}^N \left(\frac{d[\Delta Prod_i(k+1|k)]}{d\Delta P_i} - \frac{d[\Delta Prod_j(k+1|k)]}{d\Delta P_j} \right)^2 \right]$$

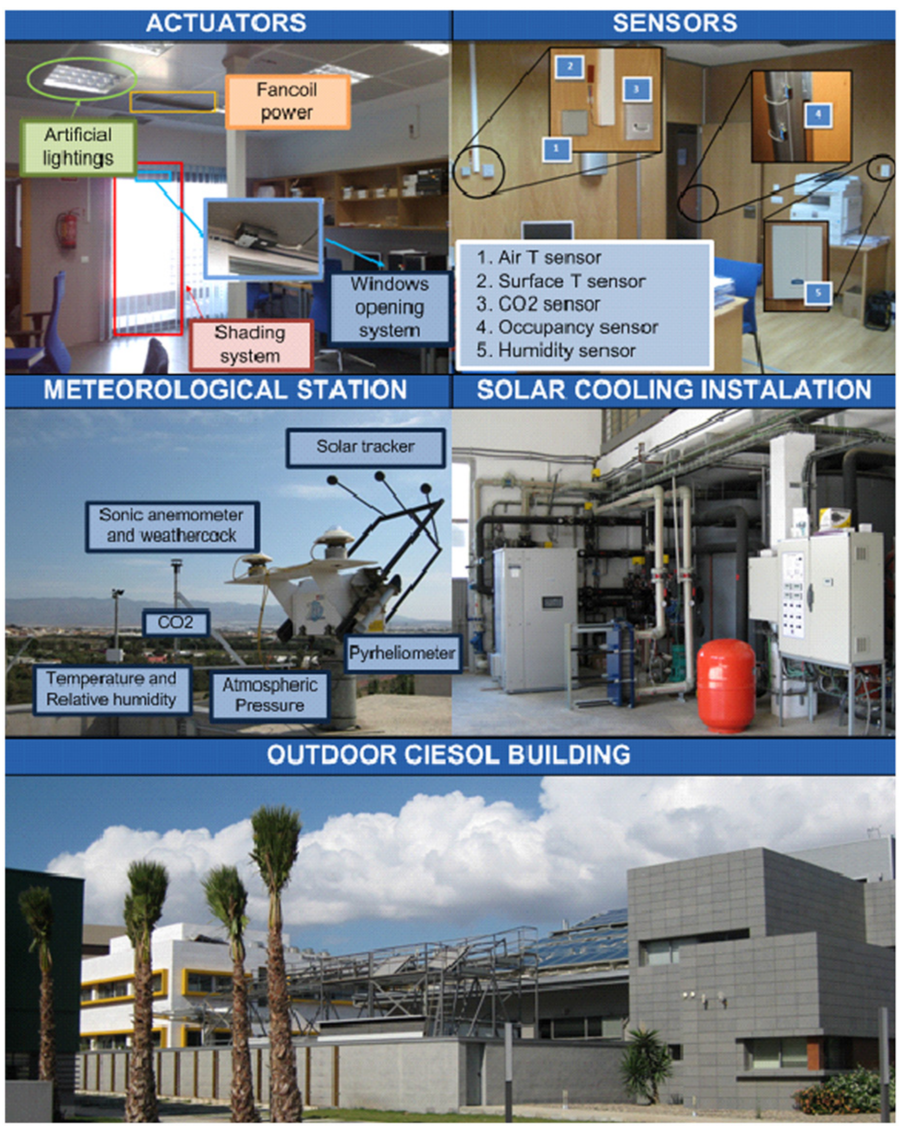

Fig. 4. CDdI-CIESOL-ARFRISOL building.

$$\text{Subject to}: \sum_{i=1}^{N} \Delta P_i(k) = \Delta P_T(k_0) \tag{4}$$

3.2. Optimisation of total production

The total production is defined for each process i (Eq. (5)). This is caused by all power of process i and it is not caused only by the controller effect, as in previous the Section (3.1).

$$Prod_i = p_i P_i T_m \quad (€) \tag{5}$$

The total production associated with productiveness is considered the sum of the total production of the N charges. This function J_2 is optimised, subject to a constant total power ($P_T+\Delta P_T$), and equal to the initial variation at the time point k_0. It takes the following form (Eq. (6)):

$$\forall\, k \mapsto k_0 \le k \le (k_0 + k_e)$$

$$Max\ J_2 = \left[\sum_{i=1}^{N} \mathrm{Prod}_i(k+1|k)\right]$$

$$\text{Subject to}: \sum_{i=1}^{N} P_i(k) = P_T + \Delta P_T(k_0) \tag{6}$$

3.3. Research framework. Description of loads

This study was made under the project entitled Predictive Control Techniques for Efficient Management of Micro-Renewable Energy Network (POWER) DPI2010-21589-C05 funded by the Ministry of Science and Innovation, and involving two research groups of the University of Seville, University of Valladolid, CIEMAT Solar Platform and the University of Almería, all in Spain.

For the control approach developed in this work to be tested, it was necessary to use a model which represents the behaviour of indoor air-temperature dynamics as a function of the HVAC system power and the outside air temperature. This approach has been applied in a simulation to a typical room of the CDdI-CIESOL-ARFRISOL building [13,15], although the results could be easily extrapolated to any room with a suitable sensors network and a HVAC system.

The CDdI-CIESOL-ARFRISOL research centre on solar energy (http://www.ciesol.es), (see Fig. 4), is a mixed centre between CIEMAT (http://www.ciemat.es/) and the University of Almería (south-eastern of Spain).

Furthermore, the model developed is associated with a characteristic room of the CDdI-CIESOL-ARFRISOL building [9,11] and its properties are listed in Table 1. More specifically, the resulting model is a nominal linearised model around a typical operation point and its main parameters have been determined by means of classical identification techniques. Eq. (7) shows the discrete-time transfer function is shown [13,48]:

$$T(t) = e^{-\frac{T_S}{\tau}} T(t-1) + \left(1 - e^{-\frac{T_S}{\tau}}\right)\left(T_O \pm \frac{P}{A}\right) \tag{7}$$

Table 1
Characteristics of rooms to cool, CIESOL.

Room volume:	$V = 45\ \mathrm{m}^3$
Coefficient of thermal losses:	$A = 0.022\ \mathrm{kW}\ ^{\circ}C^{-1}$
Desired temperature:	$T_D = 24\ ^{\circ}C$
Temperature with the equipment disconnected:	$T_{OFF} = 27\ ^{\circ}C$
Mean power of the air conditioner:	$P = 0.12$ kW
Outdoor reference temperature:	$T_O = 28\ ^{\circ}C$
Cost of the energy unit kWh:	$c_0 = 10\ c€$
Sampling period [6]:	$T_S = 5$ min

Fig. 5. Electric car of University of Almería (SE Spain).

Table 2
Characteristics of accumulator.

State of total charge:	$SoTC = 16$ kWh
Maximum power of the charge: (230 V at 20 A)	$P_{max-char} = 4$ kW
Maximum power of the discharge: (230 V at 20 A)	$P_{max\text{-}dischar} = 4$ kW
Minimum state of charge:	$SoC_{min} = 4$ kWh
Start time of the charge:	$t_S = 0$ min
Desired charge time:	$t_D = 350$ min
Cost of the energy unit kWh:	$c_0 = 10\ c€$
Sampling period [6]:	$T_S = 5$ min

where T is the indoor temperature, τ is the inertia constant, To is the outdoor reference temperature, A is a coefficient of thermal losses and P the power of the process, $(-)$ implying a cooling process and $(+)$ a heating process.

For a load described in Table 1.

The environment described in Section 3.3 also considers energy management of electric vehicles. The electric vehicle type used in University of Almería is presented in Fig. 5. Its data are listed in Table 2.

4. Simulation and discussion

The problem presented in Section 3 is solved for the two types of loads described: thermal (HVAC) and electric vehicle batteries. The problem applies only to loads of the same nature, and to do so the parameters on the load type described in Section 3.3 were modified. That is, the power was reduced for two thermal loads with different parameters and the problem was solved using different strategies: equality of partial-production rates and optimisation of total production. The same is detailed below in reference to accumulators and this paper does not apply to mixed loads (thermal loads vs. accumulators).

4.1. Thermal loads (HVAC)

Several scenarios with different disturbances have been tested simulating with different loads (rooms of CIESOL building) as:

- Different loss coefficients A, $A_1 > A_2$.
- Different temperature of the disconnected process, T_{OFF}.
- Different volume room, V.

In order to do not extend this paper, it will be presented only the problem of the reduction of 40% in power for 15 min to be distributed between loads 1 and 2 with different loss coefficients (only the first case $A_1=0.03$ kW $^{\circ}C^{-1}$ and A_2 according to Table 1 are shown). When it is solved using first strategy, equality of partial-production rates, the greater load (load 1) absorbs a higher percentage of power Fig. 6, maintaining a minor difference in final temperature. The objective is to match the variation of production per kW applied to control each load.

When the problem is solved using second strategy of solution, optimisation of total production, load 2 absorbs the entire power reduction in this case. This is because load 2 to maintain production, needs less power than does load 1 and for the optimisation of the total production, it is better to reduce the process with less power (Fig. 7). This strategy is less suitable since it solves the problem with a single load, in this case the load 2. It may be important that the load 2 is more efficient than load 1 ($A_1 > A_2$), and then, to disconnect it, the production losses will be lower.

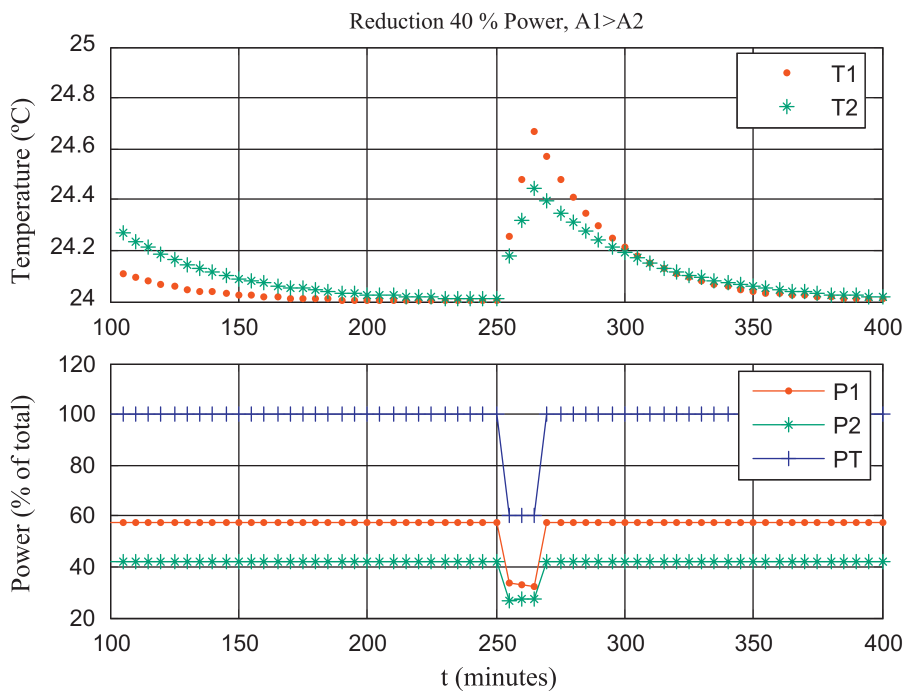

Fig. 6. Room temperature. Equality of partial-production rates, $A_1 > A_2$.

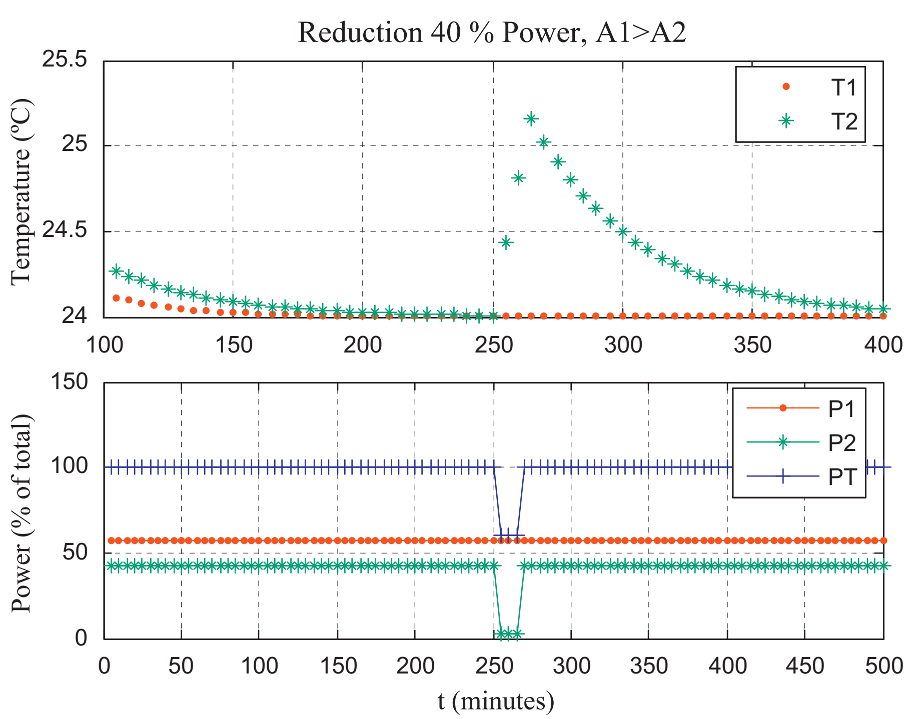

Fig. 7. Room temperature. Optimisation of total production $A_1 > A_2$.

4.2. Simulation of accumulators

Several scenarios with different disturbances have been tested simulating with different loads (batteries of electric vehicles) as:

- Different capacity *SoTC*, $SoTC_1 > SoTC_2$.
- Different instant of starting the charge, t_S.
- Different desired instant for the end of the charge, t_D.
- Different performance, η.

In order to not to extend this paper, it will be presented only the problem of the reduction of 80% in power for 50 min to be distributed between loads 1 and 2 with different capacity $SoTC_1 =$ 32 kWh and $SoTC_2$ according to Table 2.

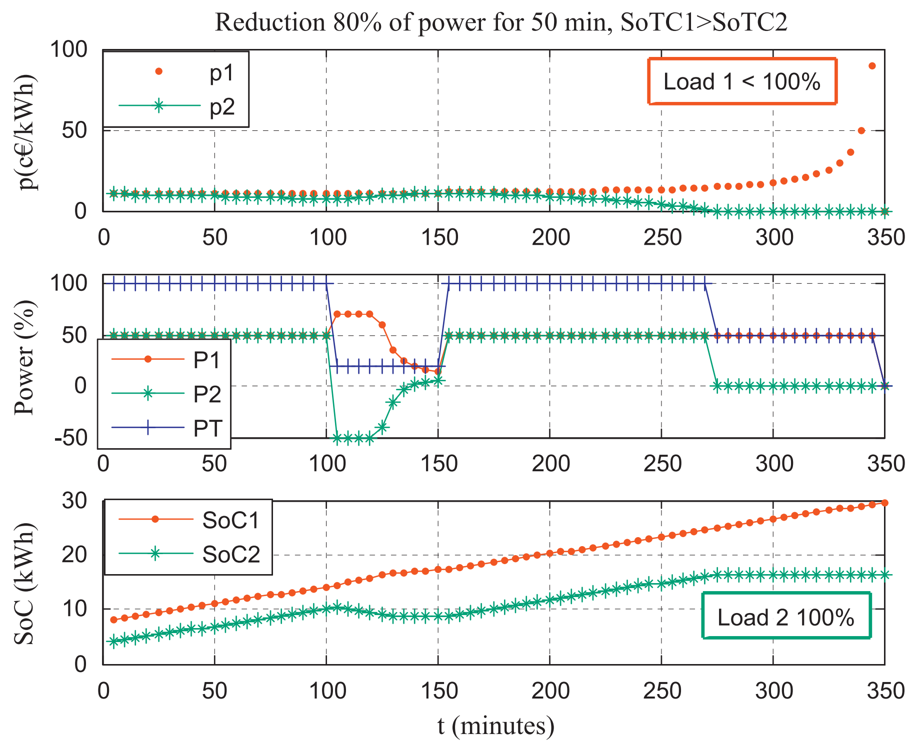

Fig. 8. Equality of partial-production rates, $SoTC_1 > SoTC_2$.

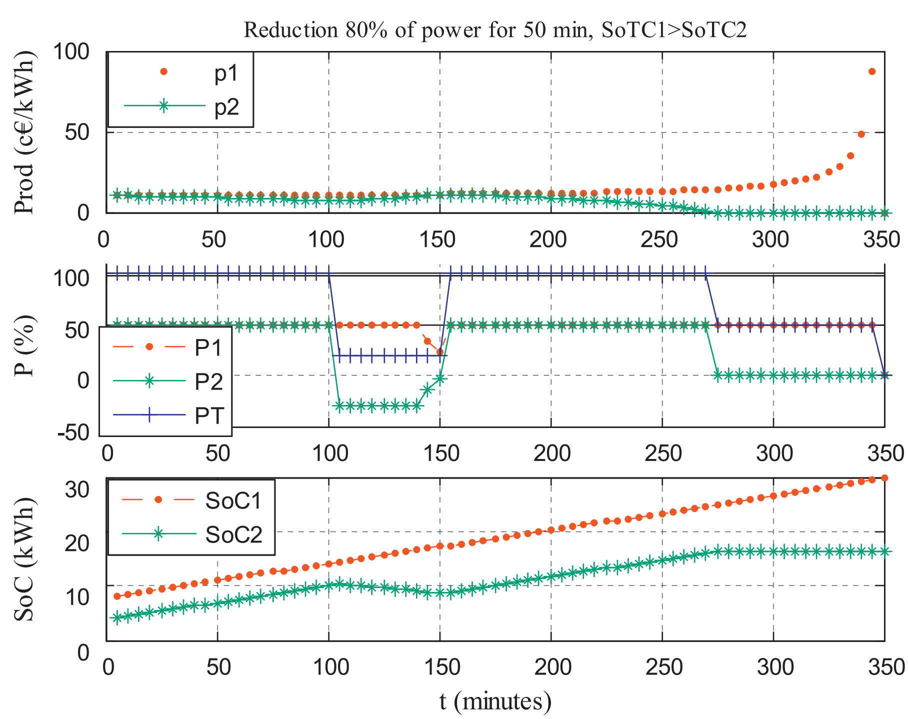

Fig. 9. Optimisation of total production, $SoTC_1 > SoTC_2$.

Fig. 8 indicates that this strategy seeks to equalise the productivity of both accumulators 1 and 2, while the contingency lasts between the instants from 100 to 150 min. At 275 min, charge 2 reaches 100% of its charge and is disconnected. It can be seen that its productivity declines instants before, since it reaches its state of total charge before the desired time (Load 2 100%). The productiveness accumulator 1 increases as it will not be able to reach its charge in the desired time, and it therefore becomes a critical charge (Load 1 $<100\%$).

When the problem is solved using second strategy of solution, optimisation of total production, results are similar to the first strategy of solution, equality of partial-production rates. Fig. 9 is similar to Fig. 8, in both cases having equal productiveness of each load due to the dependence of productiveness on the power in the accumulators is lower than in thermal loads.

5. Conclusions

The user can improve the addition of renewable resources to the electric system and this requires a method to participating in the electric-energy market. As a starting point, the concept of productivity according to the focus of this study allows the user to evaluate monetarily the use of electric energy, and this enables the management of different loads.

The concept of productiveness provides a means of reconciling the objectives of cost and quality (e.g. comfort) of the electrical energy unit. In this study, the concept has been applied to thermal loads and accumulators for electric vehicles by the strategies of equality in partial-production rates and the optimisation of total production. These evaluation functions behave differently for thermal loads but similarly in accumulators. The aim of the first control strategy is to equalise the productivity plus the effect of the control (power variation) in each of the loads. The goal of the second strategy is to optimise the overall production due to the total power of each load. In the accumulators, the variation in productivity with respect to power is lower and it can not to change significantly the state of charge of the accumulator during a sampling period (it is not the case of thermal loads). Therefore the application of both strategies in accumulators leads to the same result.

From our perspective, the concept of productiveness applied to the control strategy, equality in partial-production rates, can help in energy management by the user.

In future works, productiveness can be applied to many loads and new cost functions. Other worker-line, the strategy of equality in partial-production rates can be used by the user to establish an offer curve as opposed to the energy distributor (retailer). The first may indicate to the latter how much to appraise a rise/fall in power.

Acknowledgements

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